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Manufacturing and characterization of III-V on silicon multijunction solar cells

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Abstract

Tandem GaInP/GaAs//Si(inactive) solar cells were manufactured by direct wafer bonding under vacuum. At this early stage, an inactive silicon substrate was used (i.e. n+ Si substrate instead of an active n-p Si junction). Bonded devices presented an S-shaped *J-V* curve with a kink close to V_{oc} caused by a built-in potential barrier at the III-V//Si interface that reduces the fill factor and therefore the efficiency of the device by 7% compared to the stand-alone GaInP/GaAs tandem cells. Nevertheless, losses in J_{sc} and V_{oc} caused by the bonding process, account for less than 10%. AlGaAs single junction cells, designed to be bonded on a silicon cell for low concentrator photovoltaics (LCPV), were also manufactured reaching an efficiency of 15.9% under one sun AM1.5G spectrum for a 2 cm² cell.

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Keywords: solar cells ; photovoltaics ; multijunction ; III-V on silicon ; direct wafer bonding

1. Introduction

The refinement of mono-crystalline silicon technology has led to a record lab cell efficiency of 25.6% at one sun illumination [1], which is close to the maximum theoretical efficiency of about 29% set by the Shockley-Queisser limit [2] [3]. To overtake this limit, research using other materials and technologies is under progress, but usually

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with the drawback of higher costs, like III-V multijunction solar cells (MJSC) used in concentrator photovoltaics (CPV).

The key principle of CPV is the use of cost-efficient concentrating optics that reduces the area of expensive highly efficient MJSC, potentially allowing for a competitive levelized cost of electricity (LCOE) in some sunny areas with high values of direct normal irradiance. Double-axis tracking devices allows CPV systems to produce a larger amount of energy throughout the day, notably during late part of the day when electricity demand peaks. In addition, the use of multiple semiconducting materials in MJSC allows a more efficient conversion of photon energy from a broader range of the solar spectrum and therefore, cell efficiency is improved. This way, a record lab efficiency of 46.0% has been achieved for a four-junction cell at a concentration of 508 suns [4] thanks to the molecular bonding technology, developed by Soitec and CEA-LETI, that allows the use of III-V materials with improved bandgap configurations that could not be grown by direct epitaxy because of lattice parameter mismatch.

A possible intermediate solution to improve efficiency of silicon cells beyond 30%, but at a reasonable cost compared to high CPV, is tandem III-V on silicon cells. Detailed balance modeling shows a Shockley-Queisser limit conversion efficiency of up to 45.0% for a III-V/Si tandem solar cell with a top-cell band gap of about 1.7 eV under the AM1.5G spectrum [5]. The cost reduction can be achieved by the use of cheap and widely available silicon substrates and less expensive single-axis tracking devices for low concentration optical systems (10 to 20 suns). Furthermore, the possibility of reusing the III-V substrate [6] could lead to a low cost high efficiency photovoltaic technology [7].

The direct wafer bonding approach presented here can circumvent the problems originated from epitaxial growth of III-V on Si, like degradation of crystal quality, caused by a 4% lattice parameter mismatch and interface heterovalency, or cracks caused by the different thermal expansion coefficients [8]. However, this approach also presents a technological challenge because the III-V//Si interface that has to be electrically conductive and transparent at the same time, often contains defects or even cavities originated during the bonding process, which causes a non ohmic contact and may absorb light reducing this way the efficiency of the device.

In this work, we first describe the manufacturing process and structure of the two different devices that were characterized: an AlGaAs single junction cell designed to be bonded on a silicon cell and a dual junction GaInP/GaAs cell bonded to an inactive silicon substrate by direct wafer bonding under vacuum. Afterwards, we analyse the results and finally we explain the conclusions.

2. Single junction AlGaAs cells designed to be bonded on silicon

The growth process of III-V epitaxial wafers consisting of single junction AlGaAs cells with a band gap of 1.7 eV was done by the IIIVLab. These cells are designed to be part of an AlGaAs//Si tandem device and therefore its bandgap has been chosen to be compatible with the silicon spectral range of absorption, i.e. both cells

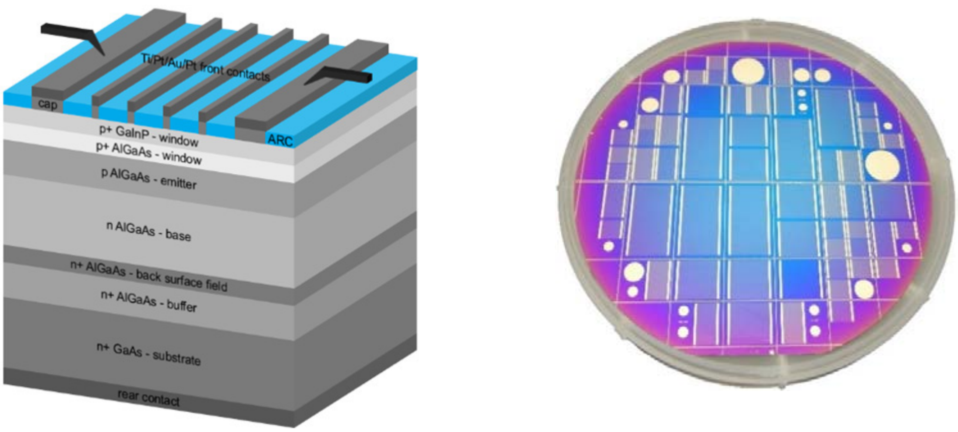

Fig. 1. (a) Not to scale scheme of a single junction AlGaAs cell showing its constituent layers and characteristics; (b) GaAs wafer of 100 mm in diameter after manufacturing of AlGaAs single junction cells of different sizes (20x10mm^2, 10x10mm^2, 10x5mm^2, 5x5mm^2).

generating the same current under AM1.5G spectrum. For this reason, the efficiency of this cell is expected to be lower than that of a GaAs solar cell with a near-optimum bandgap of ~1.42eV for stand-alone operation, which exhibits a record efficiency of 27.6% under one sun illumination [9].

The wafers are then processed at CEA and a Ti/Pt/Au metallization is done by vapor deposition over the front and back side. Afterwards, the different cells are isolated with respect to each other by 10 μm deep 200 μm wide dry plasma mesa etching. The non-covered cap layer is then removed by wet chemical etching. Finally, an ARC of SiN_x is deposited by plasma-enhanced chemical vapor deposition (PECVD) over the entire wafer. A not to scale scheme showing the structure of the cell and the finished wafer with the different isolated devices are shown in Fig. 1.

3. Dual junction GaInP/GaAs cells bonded to inactive silicon substrate

The growth process of III-V epitaxial wafers consisting of dual junction GaInP/GaAs cells, with respective bandgaps of 1.9 eV and 1.4 eV, was done by the FhG-ISE from a lattice matched GaAs substrate, thus obtaining a good crystal quality. A tunnel junction grown between the top and middle cells connects them in series. Another tunnel junction is grown at the end of the III-V stack in order to do the connection with the silicon bottom cell.

Stand-alone GaInP/GaAs cells were manufactured with this structure to be used as a reference following the same steps as in the single junction AlGaAs cells.

In the case of the bonded devices, the tandem GaInP/GaAs cells are grown upside down in an inverted configuration. Then at CEA, the III-V top surface is planarized and cleaned in order to enable the bonding process. Afterwards, the III-V cells are flipped and bonded hydrophilically in vacuum conditions at room temperature to the inactive silicon substrate. Then, they are annealed at 200°C under nitrogen. Defects and even cavities are formed at the GaAs//Si interface due to surface defectivity and surface reactivity as shown by scanning acoustic microscopy (SAM), Fig. 2. Finally, the GaAs substrate is removed from the top of the flipped III-V cells and then the integration process is done in the same way as explained before, with the exception of back side metallization that is done over the silicon substrate instead.

4. Results and discussion

In Fig. 3 the *J-V* curves of the best cells measured at one sun illumination with the AM1.5G spectrum are shown. AlGaAs single junction cells reach an efficiency of 15.9% and have a high fill factor (*FF*) of 84% due to low series resistances and good crystal quality.

GaInP/GaAs//Si(inactive) tandem cells present an S-shaped *J-V* curve with a kink close to the open circuit voltage (V_{oc}) that causes a low *FF* and results in a low efficiency of 9.0%. This is most probably due to a built-in potential barrier for majority charge carriers generated in the GaAs//Si interface that forms a parasitic reverse diode. Nevertheless, losses in short-circuit current density (Jsc) and Voc account for less than 10% compared to the stand-

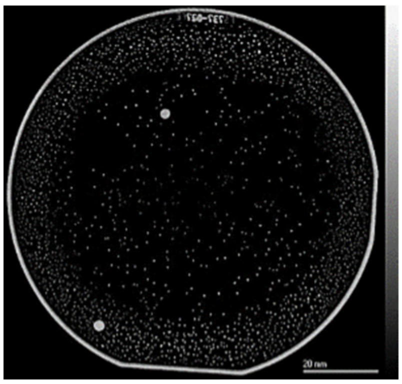

Fig. 2. Image of the GaAs/Si interface taken by SAM at 230 MHz. The white spots represent defects and even cavities at the interface.

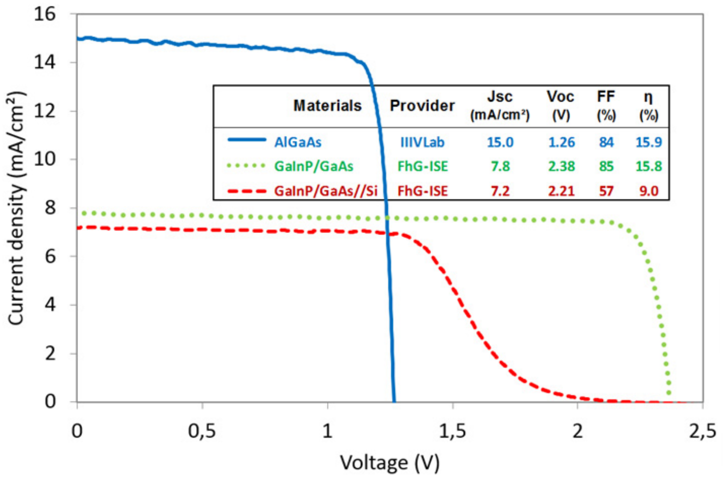

Fig. 3. *J-V* curve at one sun AM1.5G spectrum of the best AlGaAs single junction cell measured and tandem GaInP/GaAs//Si(inactive) cell along with the GaInP/GaAs stand-alone version used as reference. The measured values of J_{sc}, V_{oc}, *FF* and η are also shown.

alone GaInP/GaAs tandem cells, which reach an efficiency of 15.8%.

These first results are still far from the high efficiency objective of this III-V on silicon technology. However, we must take into consideration the fact that, at this early stage, the bonding was done on an inactive silicon substrate.

In Fig. 4 the measured external quantum efficiency (EQE) of the different cells studied is presented. For the AlGaAs single junction cells values of EQE are high, reaching 70% to 80% for a wide wavelength range from 470 to 700 nm. However, the EQE is weak for wavelengths under 450 nm indicating that the carriers generated by the high energy photons that are absorbed in the first layers of the cell, near the front surface, are not being well collected. This is interpreted as an effect of the GaInP/AlGaAs window layer that is probably not totally transparent and may be absorbing these high energy photons impeding them to reach the emitter. Therefore, the charge carriers generated at the window layer recombine near the front surface.

In the case of the tandem GaInP/GaAs//Si(inactive) cell, the top GaInP cell absorbs high energy photons above 1.9 eV (wavelengths under 650 nm) and the bottom GaAs cell absorbs the remaining low energy photons above 1.4

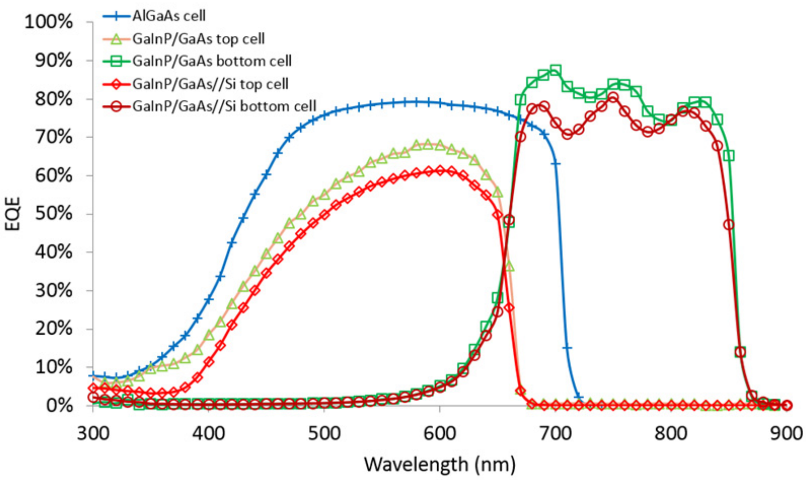

Fig. 4. EQE of AlGaAs single junction and tandem GaInP/GaAs//Si(inactive) cells along with the GaInP/GaAs stand-alone version used as reference.

eV (wavelengths under 885 nm). The impact of the bonding process is moderate causing a degradation of EQE of only ~7% compared to the stand-alone GaInP/GaAs cell. However, the differences in the layer structure between the stand alone cell (direct structure) and the bonded cell (inverted structure) do not allow to attribute the degradation in performance only to the bonding process. In both cases absorption at low wavelengths by the top cell is low. This could be caused by a degradation of the top layers or a not effective passivation causing a high surface recombination.

5. Conclusions

III-V on silicon dual or triple junction cells have potential to boost the silicon cell efficiency beyond 30% at a moderate increase of the cell cost. This structure is being considered for low concentration applications as a high-efficient and low-cost alternative to flat-plate and HCPV systems. In this paper we describe the progress on two particular activities related to this on-going research: the development of an AlGaAs single junction cell designed to be bonded on a silicon cell and the direct wafer bonding under vacuum of a dual junction GaInP/GaAs cell onto an inactive silicon substrate.

AlGaAs single junction cells grown on GaAs substrates and designed to be bonded on a silicon cell have been fabricated and characterized, demonstrating an efficiency of 15.9% under one sun illumination AM1.5G spectrum for a 2 cm² cell. EQE measurements show a good absorption and collection for a wide wavelength range. However, low EQE has been measured for wavelengths under 450 nm, probably due to recombination at the front surface caused by absorption of high energy photons in the GaInP/AlGaAs window layer. Improvement of the collection efficiency at low wavelengths will be pursued in future designs by the implementation of a new window layer with higher band gap in order to reduce the absorption of this layer.

In order to investigate the III-V on silicon wafer bonding under vacuum, GaInP/GaAs//Si(inactive) tandem cells have been manufactured, demonstrating an efficiency of 9% under the same area and illumination conditions. The main reason for this low efficiency is the low *FF* caused by an S-shaped *J-V* curve with a kink close to V_{oc} due to defects in the III-V//Si interface. Nevertheless, losses in J_{sc} and V_{oc}, caused by the bonding process, account for less than 10%.

In order to achieve our final goal of developing a high efficient AlGaAs//Si(active) dual junction cell, we are currently investigating the bonding of an optimized AlGaAs single junction cell on an active silicon cell. For that, the wafer bonding process of III-V on silicon is being optimized to obtain a III-V//Si interface without defects, electrically conductive and transparent. To achieve this we are working on different axes: modification of the atmosphere, new materials for the bonding layers, better surface preparation and different bonding techniques like ion beam surface activated bonding for instance.

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